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The goal of this project is to develop novel configurations of heat pumping elements and heat exchangers for thermoacoustic heat engines. The approach will be to use anisotropic systems, such as made possible by glass capillary array technology. This approach will allow a heat exchange fluid to flow directly across the heat pumping element of the thermoacoustic heat engine (the ''stack"), eliminating the necessity of separate heat exchangers and possibly improving efficiency. The feasibility of the approach has been demonstrated with numerical calculations, and a major milestone has been the successful fabrication of a test prototype of an anisotropic stack/heat-exchanger unit.

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ANISOTROPIC HEAT EXCHANGERS/STACK CONFIGURATIONS FOR THERMOACOUSTIC HEAT ENGINES

This annual summary report presents the accomplishments for ONR grant N00014-93-1-1127,"Anisotropic heat-exchangers/stack configurations for thermoacoustic heat engines". The goals are to eliminate the necessity of separate heat exchangers at the ends of the heat pumping element (the "stack") of a thermoacoustic heat engine, thereby improving efficiency and simplifying the fabrication of the engine. Of particular interest is the application to a thermoacoustic refrigerator (TAR). The approach will be to use glass capillary array technology to form an anisotropic unit, allowing the oscillatory flow of the thermoacoustic fluid in one direction combined with the flow of a heat exchange fluid in a perpendicular direction. A major milestone has been the successful fabrication of a test prototype of an anisotropic stack/heat exchange element.

General developments

A physics graduate student, David Zhang, has been working on the thermoacoustic refrigerator project for two years. This year he successfully completed the graduate course on thermoacoustic heat engines taught by Professor Steven L. Garrett. He has significantly improved his laboratory, machine shop, and communication skills; the latter skill has been crucial in our research, as it is necessary in order to obtain non-standard information about the glass capillaries, metal alloys, etc. required for the project. David should be commended for his successful fabrication of the first anisotropic stack/heat-exchanger, because it has involved techniques completely new to our laboratory.

Because of the patentable nature of this research, no papers or talks were presented.

Background

A major contributor to the depletion of the earth's ozone layer is the reaction of the ozone with chlorofluorocarbons (CFC's) which are released into the earth's atmosphere from refrigerators which leak CFC's. In order to satisfy current and anticipated regulations governing the use of CFC's, it will be necessary to develop new types of refrigerators which do not use CFC's. A promising technology involves the thermoacoustic effect, in which the oscillatory motion of a gas in an acoustic field is coupled to a temperature gradient at a solid surface parallel to the motion. Reviews of this effect and its application in refrigerators and other heat engines (some nearing commercialization), are available in the literature.[1,2]

In order to increase the heat carrying capacity of the thermoacoustic heat engine, a large number of solid surfaces are used in a parallel configuration, as in a stack of plates, a spiraling sheet, or an array of capillaries; this part of the thermoacoustic heat engine is referred to as the "stack". At each end of the stack are heat exchangers which would connect the refrigerator to an ambient temperature reservoir and to the load to be cooled. The sealed acoustic resonator is filled with a non-CFC gas, such as a helium-argon mixture. It should be noted that the spacing of the surfaces in the stack (or the inside diameter

of capillaries in an array) is on the order of the thermal penetration depth for the gas, typically a few hundred microns.

Key elements in a high power thermoacoustic refrigerator are the heat exchangers at the ends of the stack. For an isothermal heat-exchanger, the length of the exchanger (in the direction of the gas particle velocity) should be on the order of the gas particle peak-to-peak displacement (as large as several millimeters). A difficulty arises from the disparity in the length scales between the stack (with a scale of several hundred microns) and the heat exchanger pipes (with a scale of several mm). The TAR could be improved if the heat-exchanger were incorporated into the stack with a matching length scale. This would form an anisotropic stack/heat-exchanger unit, which could transport large heat flows laterally (across the stack) but not longitudinally (along the stack). If such a heat-exchanger used a flowing fluid, rather than heat conduction, to transport the heat, then one could not only handle higher heat loads, but one could also have graded exchanges with the external heat exchangers. That is, the temperature of the heat-exchanger fluid entering and exiting the external heat-exchanger could be made to match the temperature at the point of entry or exit of the exchanger in the stack.

The Test Prototype Anisotropic Stack/Heat-exchanger Unit

The anisotropic stack/heat-exchanger unit which we have fabricated is illustrated in Fig. 1c. The stack is composed of 50 mm long, 600 μm diameter glass capillaries, with $\sim$50 μm wall thickness, fused into a square array. The capillaries have flattened sections near each end, forming an array of 2 mm long, $\sim$100 μm wide slits passing through the stack. The thermoacoustic fluid oscillates inside the capillary pores, and a heat-exchanger fluid flows at right angles through the narrow slits between the capillaries. The heat to or from the thermoacoustic fluid near the ends of the stack conducts through the thin walls of the capillaries, and is transported by the heat-exchange fluid.

The Method of Fabrication for the Anisotropic Stack/Heat-exchanger Unit

Originally, the method for fabricating the anisotropic stack/heat-exchanger unit was envisioned as drawing a clad optical fiber so as to have precisely positioned necked-down regions, cutting these into sections, and bonding the sections into an array analogous to Fig. 3c. A final step would be to leach out the inner core of the clad optical fiber. However, during the past year a different method, which uses only commercial straight glass capillary, was conceived, as follows.

The current method for fabricating the anisotropic stack/heat-exchanger unit is illustrated in Fig. 3a through 3c. The prototype unit is formed in a frame with inside dimensions of 10 x 15 x 50 mm. 2 mm wide slots, shown with protruding strips in Figs. 1a and 1b, are positioned where the array of heat-exchanger slits will be located. The fabrication procedure is to place one layer of glass capillary sections longitudinally (along the 50 mm dimension) in the frame, followed by a flat metal strip (2 mm width and 100 μm thick) across the capillaries, passing through each set of slots at the ends of the frame. Layers of the glass capillaries and metal strips are added alternately to fill the frame. It should be

(a)

(b)

(c)

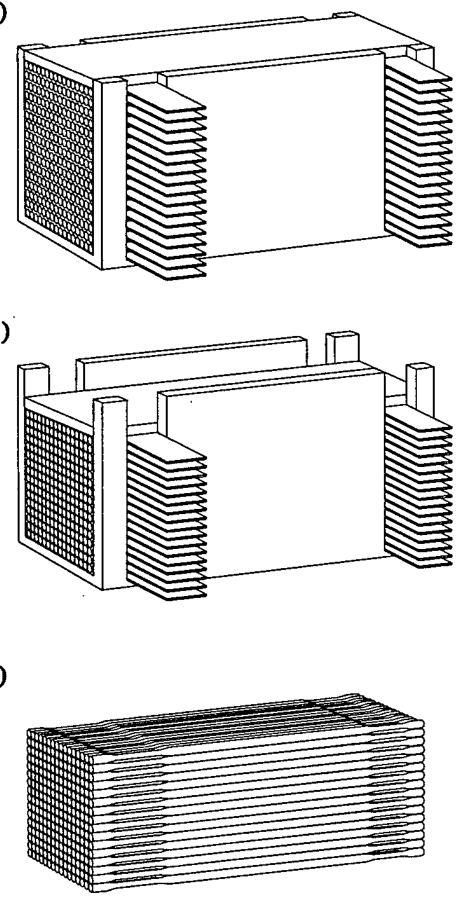

Fig. 1. An illustration of the method for fabricating the anisotropic stack/heat-exchanger unit using glass capillaries.

noted that at this point the glass capillaries are not close-packed, and the cross-section of the array is not square, because the layers of capillaries are separated by the thickness of the metal strips, as shown in Fig. 1a. This configuration of capillaries and metal strips is covered with a metal plate which is lightly spring loaded so as to compress the capillary and metal strip array. The entire assembly is placed on a slowly rotating shaft inside a furnace and heated to slightly below the softening temperature of the glass ($\sim$800 C). The heating is done in an inert gas atmosphere to avoid excessive oxidation of the metal surfaces. With gradual heating, the capillary array eventually flows into the configuration shown in Fig. 1b., where the glass capillaries now form a square close-packed array, and in the region of the metal strips the circular cross-section of each capillary deforms into a rectangle. A simple calculation based on a perimeter preserving deformation shows that the metal strips may occupy as much as 2 - $\pi/2$ or $\sim$43% of the height of the array. The next step in the process is to place the assembly in acid and remove all of the metal, leaving the glass capillary array, with open slits for the heat exchange fluid, as shown in Fig. 3c. The final step (not yet undertaken in our research) would be to epoxy the unit into a manifold so that the unit could be mounted into an acoustic resonator and heat-exchanger

fluid connections could be made.

The fabrication method outlined above required considerable prior study, particularly in the selection of materials. For example, readily available quartz capillary could not be used because its softening temperature ($\sim$1600 C) was so high that it severely limited the metals which could be used for the frame and strips; most metals would melt before the quartz softened. Borosilicate (Corning glass code 7740) glass, which softens at $\sim$800 C, was necessary, and with considerable effort, a company which sold thin-walled borosilicate glass capillary was located.

Metal removal techniques often use aluminum, which dissolves in NaOH, but aluminum melts at 649 C, and hence could not be used even with the borosilicate glass. Many high melting temperature metals are not readily dissolved, or are not sufficiently stiff to remain flat when used for the metal strips crossing the capillary array. After a considerable search, a cupronickel alloy was selected.

There were many parameters which needed testing for the successful fabrication of the glass capillary unit, such as the amount of spring loading of the top plate, the time and temperature for the glass softening, etc. While a test prototype was successfully fabricated, considerable more research is necessary to form a larger, leak tight, unit in a manifold, but the method seems very promising.

Current and Other Funding

Other research grants include:

1. NSF Division of Materials Research, Condensed Matter Physics Program, DMR 93-06791, 249,000/3 yr, which includes 1 man-month of the principal investigators time.

2. ONR, Physics Division, N00014-92-J-1186, November 1, 1991 to October 31, 1994, 300,000/3 yr, "Innovative acoustic techniques for studying new materials and new developments in solid state physics"; includes 1 man-month of time for the principle investigator.

3. ONR, Physics Division, N00014-93-1-0779, June 1, 1993 to May 31, 1996 105,000/3 yr, "Training students in new acoustic techniques for studies of fracture and nondestructive evaluation of exotic materials"; includes no time for the principal investigator.

References

1. G. W. Swift, J. Acoust. Soc. Am. **84**, 1145 (1988). Thermoacoustic engines.

2. G. W. Swift, *Physics Today* , July 1995, p. 22.